A STUDY OF SURFACE, 50 METER AND 200 METER TEMPERATURE AND SALINITY FLUCTUATIONS AT OCEAN WEATHER STATION NOVEMBER, 1968-1970

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THESIS

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June 1973

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Submitted in partial fulfillment of the
requirements for the degree of

MASTER OF SCIENCE IN OCEANOGRAPHY

from the

NAVAL POSTGRADUATE SCHOOL
June 1973

ABSTRACT

Long and short-term surface, 50 and 200 meter temperature and salinity fluctuations at Ocean Weather Station November during 1968 through 1970 were examined using several statistical techniques. One technique, a unique monthly bi-variate modal analysis of surface temperature and salinity, proved to be a valuable research tool in that the resulting monthly modal cells, when plotted on a T-S diagram, provided a simplified view of the annual T-S relationships. The average range of mean monthly temperatures at the surface was found to be 5.6° C and 4.0° C at 50 meters. Salinity at both the surface and 50 meters exhibited a semi-annual periodicity. Range of temperature at 200 meters was 1.5° C. The results of a seasonal linear regression analysis show that surface and 50 meter temperatures were correlated during periods of increasing or decreasing surface temperatures. Surface temperature and salinity were correlated only during the apparent advection of modified subarctic water into the region around OWS November.

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ACKNOWLEDGEMENTS

The author wishes to express his sincerest appreciation to Dr. R. H. Bourke, for his patience, guidance and advice throughout this study. Appreciation is also due to Professor Noel E. J. Boston for his review of the thesis and for his constructive comments.

To my wife, Sharon, I offer my special thanks for her encouragement and patience, without which this project would have been impossible to complete.

I. INTRODUCTION

While temporal variations of sea surface temperatures have received much attention by researchers studying the interactions between the sea and atmosphere, few such studies have been made of the simultaneous variations occurring below the surface. Even fewer studies have been made of the concurrent variations in salinity at both the surface and within the upper layers of the ocean. Yet both of these observed quantities are of great significance in that they characterize such oceanographic features as the thermo-haline structure and heat content of a water column.

Sea surface temperature is one of the parameters used to calculate energy transfers across the air-sea interface [Wyrtki, 1965]. Generally it has been the only synoptic oceanographic information available on the thermal conditions of the oceans. For this purpose, sea surface temperature variations have been studied intensely in the past.

Sea surface temperature anomalies, the differences between observed and long-term mean temperatures, have been used as an important source of information on the thermal content of the ocean. However, more recent work has shown that subsurface temperature anomalies, which often extend below 100 meters, represent a sizable

amount of heat which can affect the energy feedback system [Beland, 1971].

Surface and subsurface temperature variations are important to other oceanographic parameters as well. Changes in the thermal structure are often the dominant factor in the vertical stability of the water column. This structure is also of great consequence to the propagation of sound in the ocean. It is apparent that an understanding of the thermal response of the subsurface layers to fluctuations in sea surface temperature would be of immense value.

Similarly, fluctuations in salinity are of interest since many oceanographic parameters are a function of this quantity. Again, vertical stability and sound propagation are examples of two parameters that respond to variations in salinity, although to a lesser extent than temperature.

There have been surprisingly few published reports resulting from the study of long-term temporal variations of salinity. This most likely arises from the fact that few long-term salinity observations at any one station have been conducted due to the great expense of maintaining such a data collection program. However, this is not to deny that such studies are of great importance to the understanding of oceanographic processes within the upper layers of the oceans.

In the past due to instrument limitations, the ocean has been considered to be slowly changing or quiescent. Scientists were inclined

to rely on monthly and annual means to describe the state of the ocean. In recent years small-scale fluctuations in synoptic conditions have been used to describe significant short-term changes of state in the ocean.

The scale of short-term changes in the upper layers of the ocean correspond to the scale of the meteorological driving forces. Ignoring advection, sea surface temperature fluctuates on a day-to-day basis depending on the temperature of the overlying air mass, the amount of insolation, mixing due to wind waves and the amount of cloud-cover. The magnitude of these daily fluctuations of sea surface temperature may be as large as the fluctuations in monthly means.

Large-scale changes in oceanic properties, such as year-to-year temperature anomalies, correspond to the scale of changes in the general circulation pattern. Such macro-scale changes are of considerable magnitude and often persist in both time and space.

An examination of short-term (day-to-day) and long-term (yearly) responses of temperature and salinity in the upper layers of the north-eastern Pacific Ocean is made. Synoptic data collected by the United States Coast Guard at Ocean Weather Station (OWS) November, located at 30° North and 140° West (Figure 1) was used. Temporal variations of temperature and salinity observed at the surface, within the seasonal mixed layer and within the upper portion of the permanent thermocline were studied in an effort to gain a more complete understanding of the upper layers of the ocean and variations in sea surface temperature.

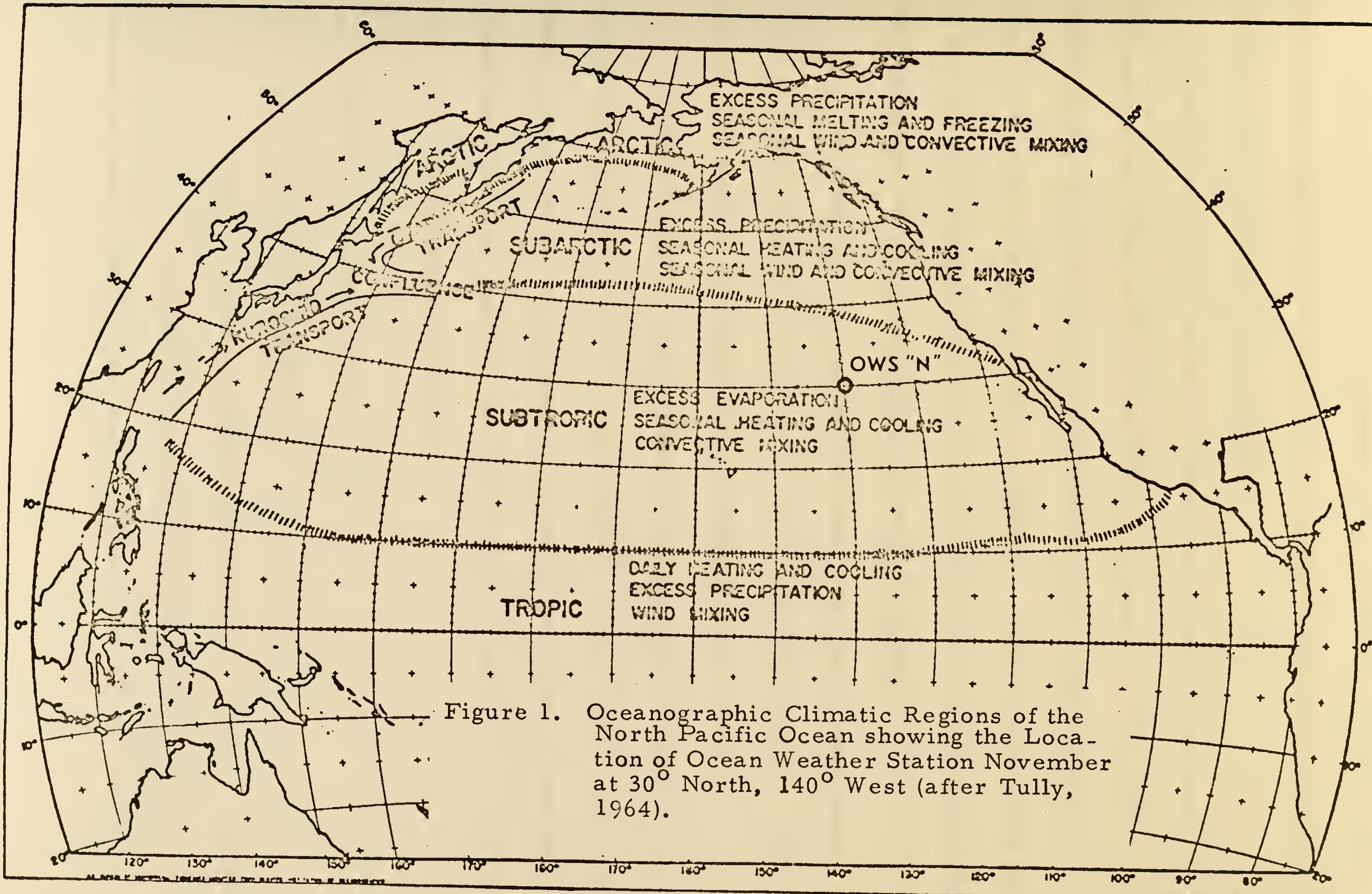

Figure 1. Oceanographic Climatic Regions of the North Pacific Ocean showing the Location of Ocean Weather Station November at 30° North, 140° West (after Tully, 1964).

Co-incidentally long-term temporal variations of surface and subsurface salinity were studied since there is an apparent gap in the literature with respect to this subject.

Indications of the response of the upper layers of the ocean to changes in heat input will be examined in two ways. First, the correlations existing between temperature at the surface and at selected depths of interest will be calculated. These correlations may be used as an indication of the relation between sea surface temperature and the temperature at a particular depth of interest.

Second, the time lag between surface temperature maximum and minimum and those occurring at depth will be determined. Such a study will yield an indication of the response time involved.

No attempt will be made to examine the synoptic atmospheric mechanisms responsible for the fluctuations of sea surface temperature. The primary concern of this thesis will be the relationship between the mixed layer and the upper portion of the main thermocline to observed sea surface temperature variations.

A. REVIEW OF THE LITERATURE

1. <u>The Subtropic Region</u>

OWS November lies within the subtropic region as defined by Tully [1964]. This region is characterized by (1) an excess of evaporation over precipitation throughout the year, (2) convective

mixing and (3) seasonal heating and cooling. It is the largest of the oceanographic regions and includes the North Pacific Gyre.

The excess of evaporation over precipitation results from the maintenance of high temperature levels at the sea surface throughout the year. Tully [1964] estimated an annual mean difference between evaporation and precipitation of about 80 centimeters per year at 30° North and 140° West.

Removal of freshwater from the sea surface by evaporation results in evaporation-driven convective mixing. The denser surface water sinks until it reaches an equilibrium level, forming a mixed layer deeper than that formed by simple wind mixing.

Seasonal heating occurs from spring to the summer equinox when daytime heating exceeds nighttime cooling. Heat accumulates at the surface until September when temperatures are at their maximum. Cooling of the sea surface dominates during the rest of the year, with the coldest temperatures occurring in March.

The seasonal growth and decay of the temperature structure of the upper layers of the subtropic region are schematically illustrated in Figure 2. The upper layer is isothermal to about 150 meters at the end of the cooling season. Warming of the near surface waters results in the formation of a seasonal thermocline between 40 and 60 meters. Continued warming results in an increase of the thermocline gradient while its depth remains nearly constant. Cooling of the surface waters

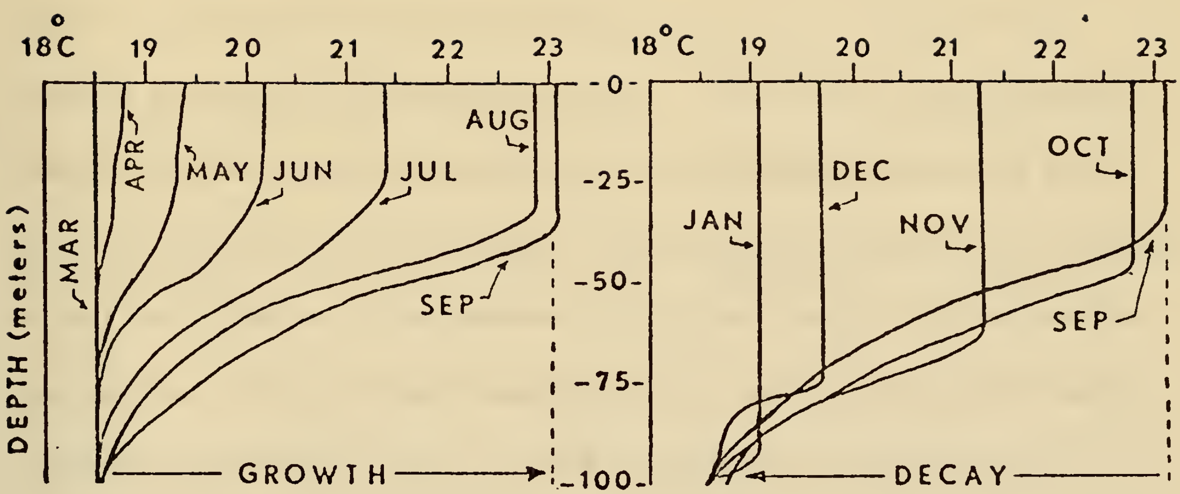

Figure 2. Schematic Representation of the Seasonal Growth and Decay of the Thermocline at OWS November (after Beland, 1971).

results in accelerated convective mixing which erodes the seasonal thermocline until isothermal conditions extending to the depth of the main thermocline are re-established [Tully, 1964].

2. Surface Circulation

The Pacific Gyre is the dominating feature of the surface circulation in the mid-latitude region of the eastern North Pacific Ocean. This gyre is wind driven and responds to changes in the general atmospheric circulation pattern. Generally, during summer the axis of the gyre is displaced more to the north than during winter. A chart showing the mean surface currents in the North Pacific during winter and summer is reproduced in Figures 3 and 4 [Department of Commerce, 1961]. From these figures it can be seen that the mean current speed ranges from 0.1 to 0.3 knots throughout the year.

The apparent intensification of the North Pacific Gyre in summer centered to the northwest of station November has several important influences on the oceanography at this location. A hypothesis is developed in a later part of this thesis that occasionally large volumes of cold subarctic water are advected into the area around OWS November. The result is significant decreases in temperature and salinity in the upper layers of the ocean. Also, there is evidence that this circulation pattern was altered during the early months of each of the years 1968 through 1970.

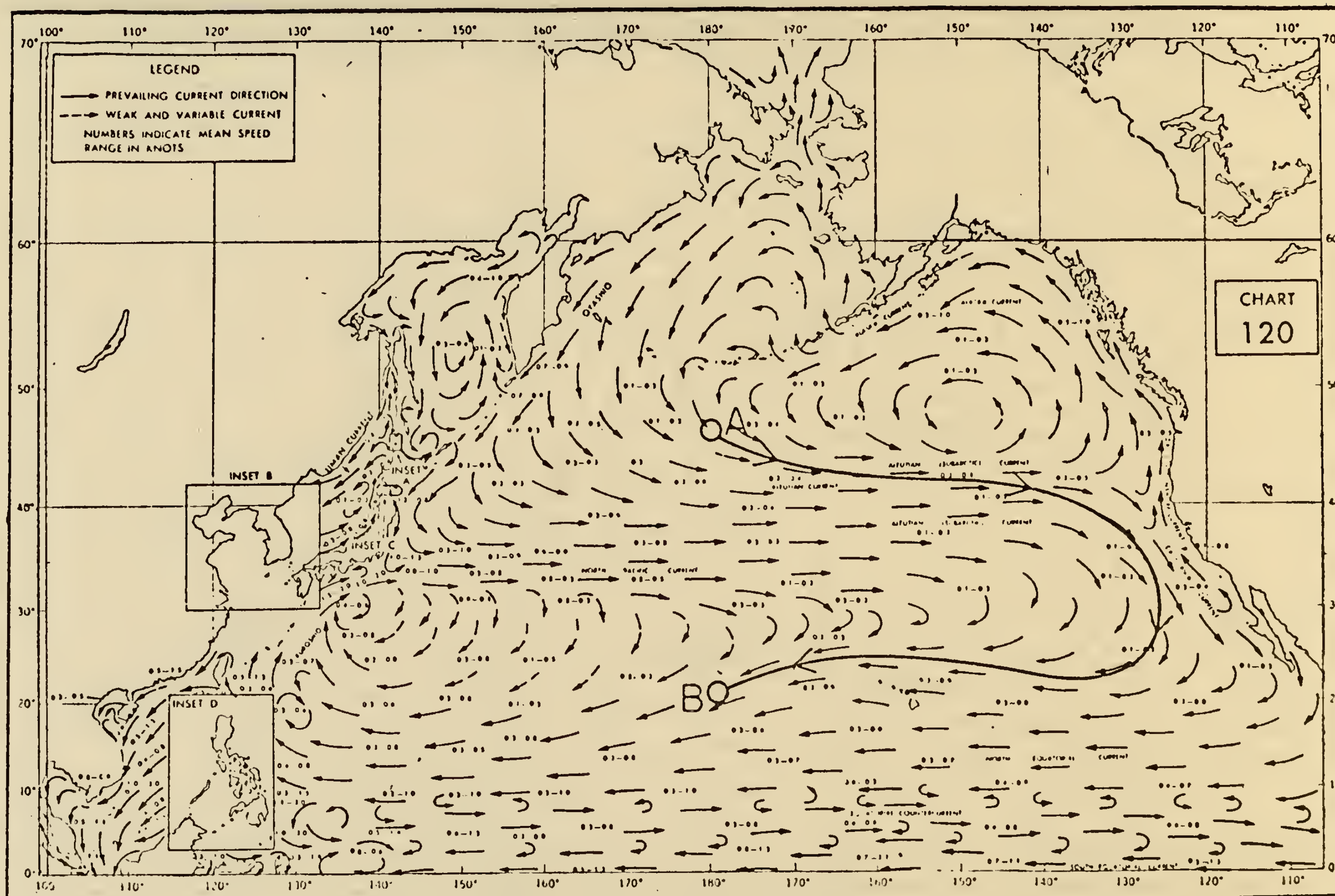

Figure 3. Winter Surface Circulation Patterns for the North Pacific Ocean (Department of Commerce, 1961).

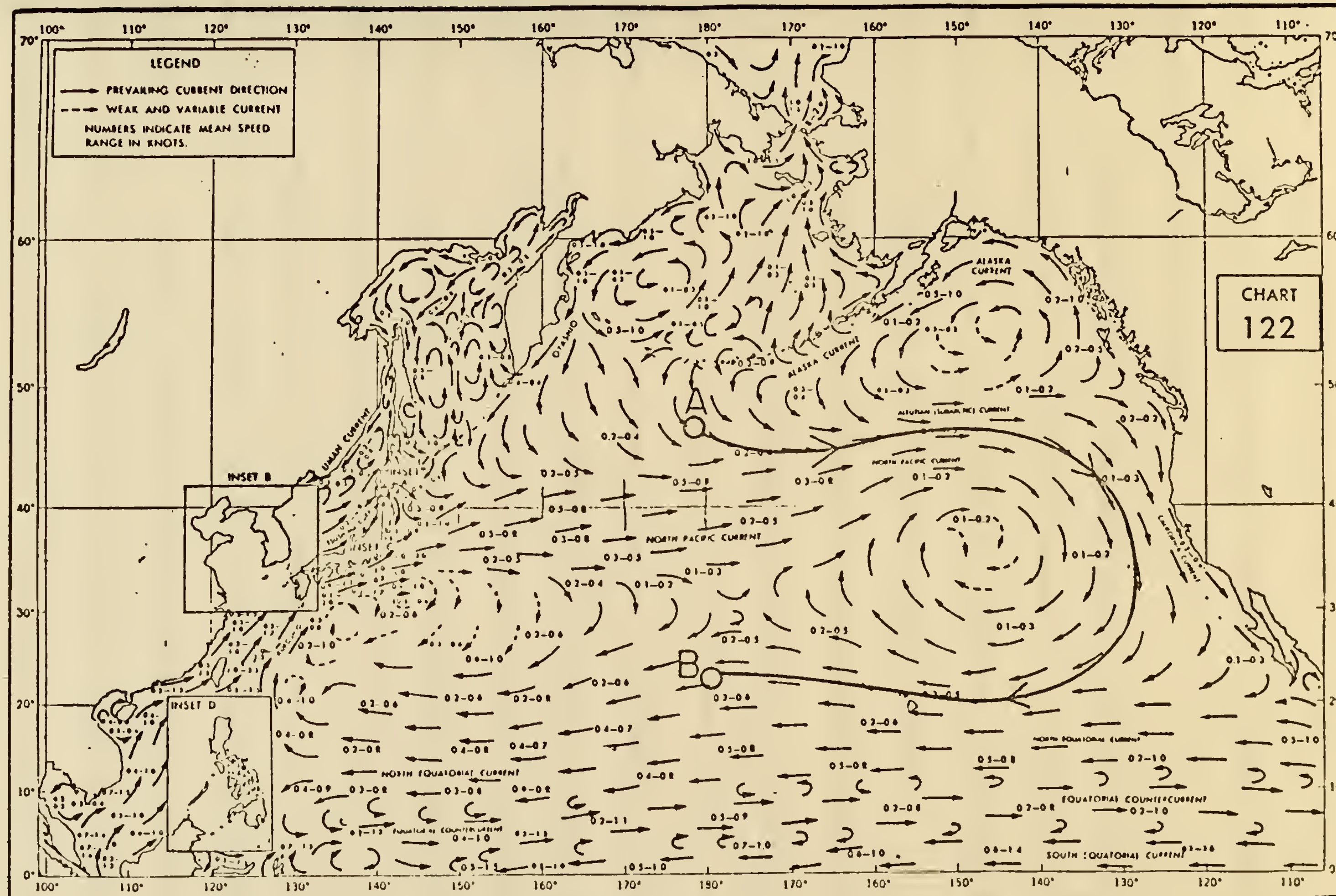

Figure 4. Summer Surface Circulation Patterns for the North Pacific Ocean (Department of Commerce, 1961).

The low speed of the currents associated with the Pacific Gyre in the area of OWS November allows the surface water to adjust to climatic conditions [Tully, 1964]. However, to some degree, the waters retain their properties.

The persistence of anomalous sea surface temperatures in the North Pacific has been studied intensively by Namias [1970]. From his studies he has made inferences regarding the transport of surface water between the Subarctic and Pacific Gyres.

He found that anomalous water generated in the Subarctic Gyre frequently enters the subtropics and persists for indefinite periods of time. He based this conclusion on seasonal sea surface temperature lag correlation studies. The magnitude of the indicated transport (0.2 to 0.3 knots) agrees well with the mean surface current charts (Figures 3 and 4). Further, he has determined that anomalously cold or warm water generated in the north in any season usually does not show up in the southern area until the fall of the same year.

Mean monthly transport computations for the North Pacific Ocean at 100 meters, based on mean monthly values of sea level pressure, are routinely computed and published annually by the Fisheries Research Board of Canada in their Technical Report series. The computed meridional component of total mass transport between longitudes 135° to 145° at 30° North for 1969 and 1970 is shown in Figure 5 [Wickett and Thomson, 1970, 1971]. Before discussing these

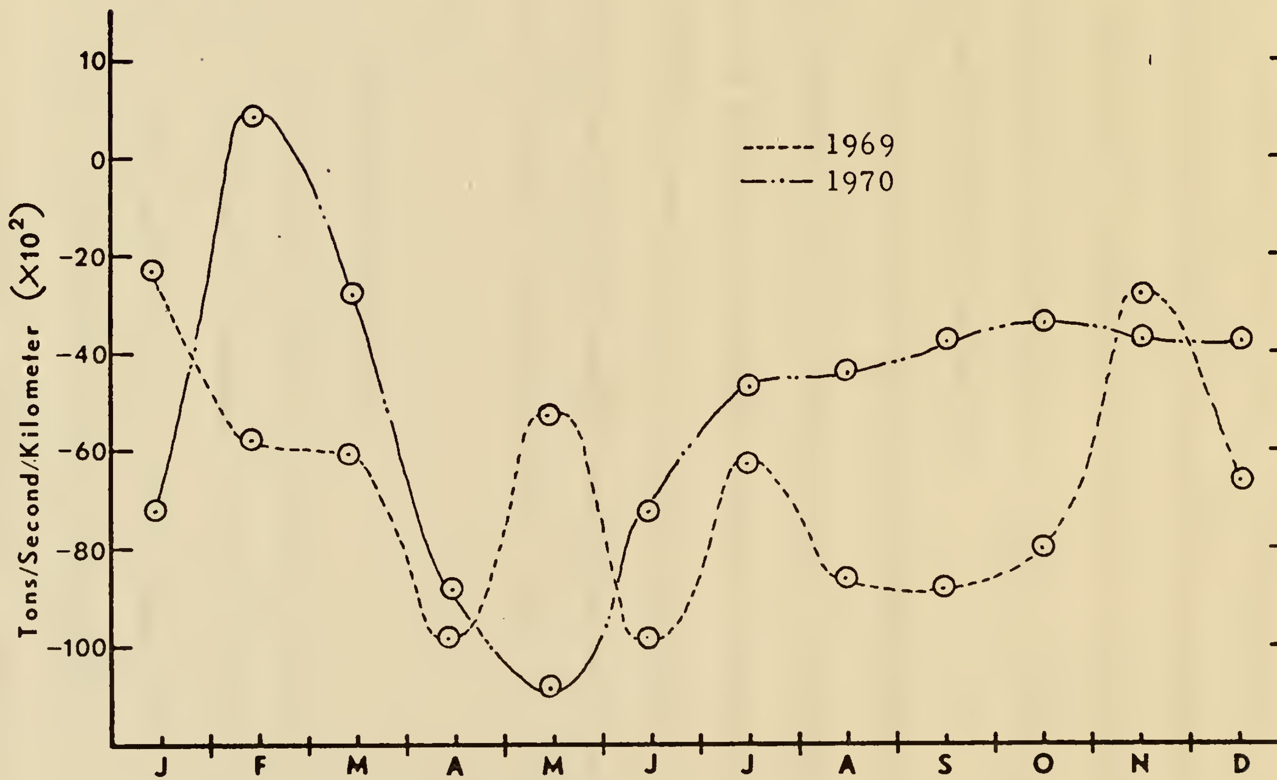

Figure 5. Total monthly Meridional Transport Between 135° and 145° West at 30° North during 1969 and 1970. Positive Northward, Negative Southward. (after Wickett and Thomson, 1970, 1971).

transport figures, it must be pointed out that the monthly calculations are carried out independently of each other. The monthly transports can be interpreted as the transport that would result if the pressure distribution for that month were to persist indefinitely. No account of inertia of the ocean is taken in going from one monthly mean to another. Therefore, the computed transport values must be interpreted as indications of tendencies of the ocean circulation and are necessarily conservative in magnitude.

It can be seen that, in general, considerable north to south mass transport occurs at various times of each year. Apparently during 1969 and 1970 most transport occurred between April and October in 1969 and between April and June during 1970. The comparatively large amount of transport towards the south noted in 1969 is noteworthy and will be discussed in more detail in a following portion of this thesis.

3. Surface Transition Zone

One of the most prominent features of the northeastern Pacific is the transition zone between the subarctic and subtropic water masses. This zone occupies a belt between 32° and 42° North in the western part of the Pacific and turns southward as it approaches the North American continent. To the north is found the subarctic water mass distinguished by its lower surface temperatures and salinities. Southward can be found water of subtropical origin, which

is higher in temperature and salinity. Between these two water masses lies the subarctic-subtropical transition zone marked by strong horizontal gradients [Roden, 1970].

The southern boundary of the transition zone was found to exist between 30° and 31° North, about the same latitude as OWS November. The principal feature of this boundary was a rather sharp transition toward higher salinities and higher temperatures characteristic of the subtropical water mass found to the south. Salinities in excess of 35 $^{\circ}/oo$ characterize the subtropic water mass in this region. Seasonal and year-to-year variations in the position of the southern boundary have been noted in the literature but have not been documented in detail.

4. <u>Average Annual Heat Balance</u>

Wyrtki [1965] examined the average annual heat balance of the North Pacific Ocean and its relation to circulation. Interpolating from Wyrtki's figures, it is apparent that the ocean gains a relatively small amount of heat during an average year in the vicinity of OWS November. In this area the upper layers of the sea absorb an annual average of 25 calories per square centimeter per day.

5. <u>Surface and Subsurface Temperature Anomalies</u>

Sea surface temperature and its anomalies have received considerable emphasis to date in both oceanographic and weather forecasting. However, only recently have subsurface temperature

anomalies received attention. Beland [1971] has indicated the considerable importance of large amounts of anomalously warm or cold subsurface waters on the flow of thermal energy between the sea and atmosphere. The presence of anomalously warm water may act as a source of thermal energy for the atmosphere. A negative anomaly may indicate the presence of a thermal energy sink for the atmosphere.

An observed anomalous warming of the northeastern Pacific from May to June, 1968, was found by Namias [1971] to be due largely to increased insolation and horizontal convergence of the surface layers of the sea and associated downwelling, with some contribution from reduced latent and sensible heat losses. The warming was associated with the development and maintenance of a Pacific anticyclone in June. This anticyclone was persistently regenerated by an unusually strong mean jet around 40° North.

The Namias study of the anomaly at Ocean Station November indicated that the warm pool of water extended to a depth of 122 meters. Bulk computations of heating, ignoring advection and mixing, accounted for one-third of the heating while the rest apparently was due to downward advection of heated water.

The warm pool was demolished during the fall and early part of 1969. Cyclonic activity was greatly amplified during this winter peiod as cold air masses, fronts and cyclones siphoned off the excess heat and moisture of the warm pool.

Clark [1972] has concluded that both advective and non-advective processes are important in determining the nature of temperature anomalies in the surface layers of the ocean. Furthermore, he states it is apparent that advective heat transfer is a more significant process in winter and spring, while non-advective processes have a more significant effect during summer and fall.

Beland [1971] found that about 50 percent of the observed surface anomalies extended to at least 100 meters. Of these, most were negative anomalies with magnitudes greater than 1.0° C. Negative anomalies were most common during March and April. He hypothesized that the greater occurrences of negative anomalies were due to the distribution of heat throughout the upper layer by convective mixing.

Positive anomalies were more common during late winter or early spring (December through February) and generally penetrated only to 30 meters or less. The magnitude of the positive anomalies were generally less than 1.0° C. Beland went on to suggest that the seasonal thermocline inhibited the conduction of heat downward resulting in relatively shallow positive temperature anomalies.

II. DATA ANALYSIS

A. THE DATA

Data used in this study were collected by the United States Coast Guard at Ocean Weather Station (OWS) November located at 30° North, 140° West in the northeastern Pacific Ocean. The original oceanographic sampling program started in 1966 consisted of daily Nansen bottle casts to 1500 meters on alternate 21-day patrols. Since 7 January 1968, however, the program has been expanded to daily hydrocasts on every patrol.

Examination of the data revealed that all data prior to 7 January 1968 contained significant time segments of missing data, some as long as several months. Therefore, the time series for this study was limited by the available data to the 3 year period from 7 January 1968 to 6 March 1971.

The data record from 7 January 1968 to 6 March 1971 contained several data discontinuities. The mean length of the missing data segments was 5.6 days. The longest break in the data was 25 days and the shortest was 2 days. All of the discontinuities were evenly distributed throughout the entire record length.

Discontinuities were eliminated by interpolation. The data at each depth of interest was hand plotted and a best fit curve drawn.

Missing data were interpolated from the curve and inserted into the original data record. All off-station, duplicate, and nonrepresentative data were replaced by interpolated values.

There were a total of 1,155 data points in the time series used in this study, 266 of these were interpolated (22%). This is not considered an excessive amount since the mean interval was relatively small and the intervals were well distributed throughout the data record.

Inductive salinometers and deep-sea reversing thermometers were used to measure salinities and temperatures. Duplicate water samples were also obtained for comparison with the surface and 1500 meter Nansen casts for quality control. It was found that on the average 89 percent of the salinity samples differed from the ship's values by less than 0.01 $^{o}/oo$ [Husby, 1969]. Accuracy of the temperature measurements was not discussed in the literature. An accuracy of plus or minus 0.01^{o} C is assumed.

The hydrocasts were normally conducted at 1100 hours local time. When two or more casts were made on the same day, the one conducted nearest to 1100 hours was retained and the remainder eliminated from the data record. This effectively eliminated diurnal effects.

B. DEPTH SELECTION

Temperature and salinity values measured at 50 and 200 meters were chosen for comparison with surface values. The decision to use these levels was based on an examination of typical OWS November vertical temperature profiles [Husby, 1968], previously mentioned schematic temperature profiles presented by Beland [1971] and solar radiation penetration data presented by Sverdrup, et al [1942]. The goal in selecting these depths was to compare and contrast fluctuations of temperature and salinity at the surface, within the mixed layer and within the main thermocline.

Station November vertical temperature profiles after Husby [1969] are shown in Figure 6. From these profiles it can be seen that 50 meters lies within the mixed layer approximately 6 months out of a year. The main thermocline is found to lie permanently above 200 meters.

C. ANALYSIS TECHNIQUES

Several analysis techniques were used during the preparation of this thesis. These techniques included calculation of annual and monthly means, monthly standard deviations, bi-variate analysis and a seasonal regression analysis.

Monthly means of temperature and salinity were calculated for the years 1968 through 1971. The means were then plotted against

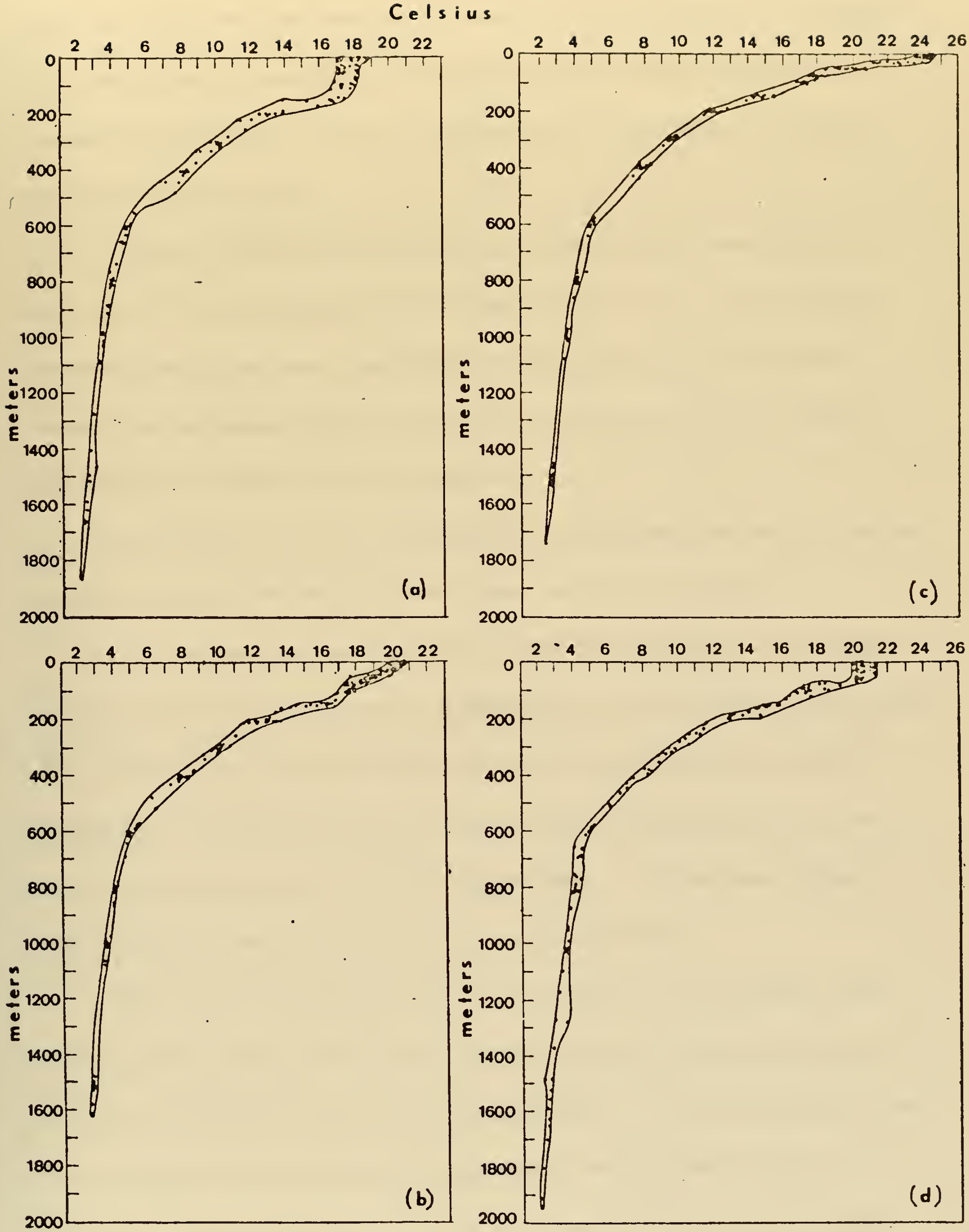

Figure 6. Seasonal Vertical Temperature Profiles at OWS November, (a) Late Winter (2-19 May, 1967), (b) Summer-to-Winter (15 Jun-1 Jul, 1967), (c) Summer (3-24 Sep, 1967), and (d) Summer-to-Winter (26 Nov-17 Dec, 1967). (after Husby, 1969).

time in order that the behavior of each property with time throughout the year could be analyzed. These plots also made it possible to compare the behavior between temperature and salinity throughout the three year period.

Standard deviations were computed in order to measure the variation of each property at each depth of interest. The unbiased standard deviation was used throughout this study. The standard deviations calculated were also used as a measure of the relative variations of temperature and salinity.

An average year was calculated by computing the daily mean of temperature and salinity for the 3 year record, 1968-1971.

A bi-variate analysis was performed to establish the seasonal characteristics of temperature and salinity over the three year period. The simultaneous modal analysis of both temperature and salinity simplified the relation between the variables so that the variation of each parameter could be readily visualized. A brief description of the technique used to perform this analysis follows.

The modes of temperature and salinity for each month of the average year were determined by summing the daily occurrence of categorized pairs of salinity and temperature. The increments used to establish the categories of temperature and salinity were 0.5 ^{o}C and 0.10 ^{o}/oo, respectively. The frequency of occurrence of each T-S cell was converted to a percentage of the total and plotted as a

scalar field on the T-S diagram. Isopleths were drawn at 2, 4 and 6 percent occurrences. The resulting monthly modes of each pair were also indicated.

A multiple linear regression analysis was performed for each season using the statistics library program, REGRE. The procedure used was to divide the three year and two month data record into seasons and perform the regression analysis on each season. Sea surface temperature was held as the dependent variable and all other variables at the surface and at the other depths were held as independent variables. A mean seasonal correlation coefficient was computed from the results.

III. RESULTS

The discussion of the results is based on the recurring sea surface temperature cycle suggested by the bi-variate analysis of surface temperatures from 1968 through 1970. The results of the bi-variate, or combined modal analysis of sea surface temperature and salinity is presented in Figure 7. From this figure it is possible to readily discern four phases of the yearly temperature cycle.

The first of these phases is the period of time when surface temperatures are the lowest. This condition persists through the months of March and April when the mode of the surface temperature is about 17.8^{o} C. This phase of the temperature cycle will be referred to as the winter period.

During the months May through July the surface temperature increased markedly. The total change in modal temperature during this transition is about 5.0^{o} C. This period of surface warming will be referred to as the winter-to-summer transition period.

The summer period, characterized by high surface temperatures of about 22.8^{o} C exists from August through October. During this period the monthly temperature mode is unchanged.

Following the summer period surface temperatures decrease. This cooling period will be referred to as the summer-to-winter transition period. This period was observed to occur from November through February.

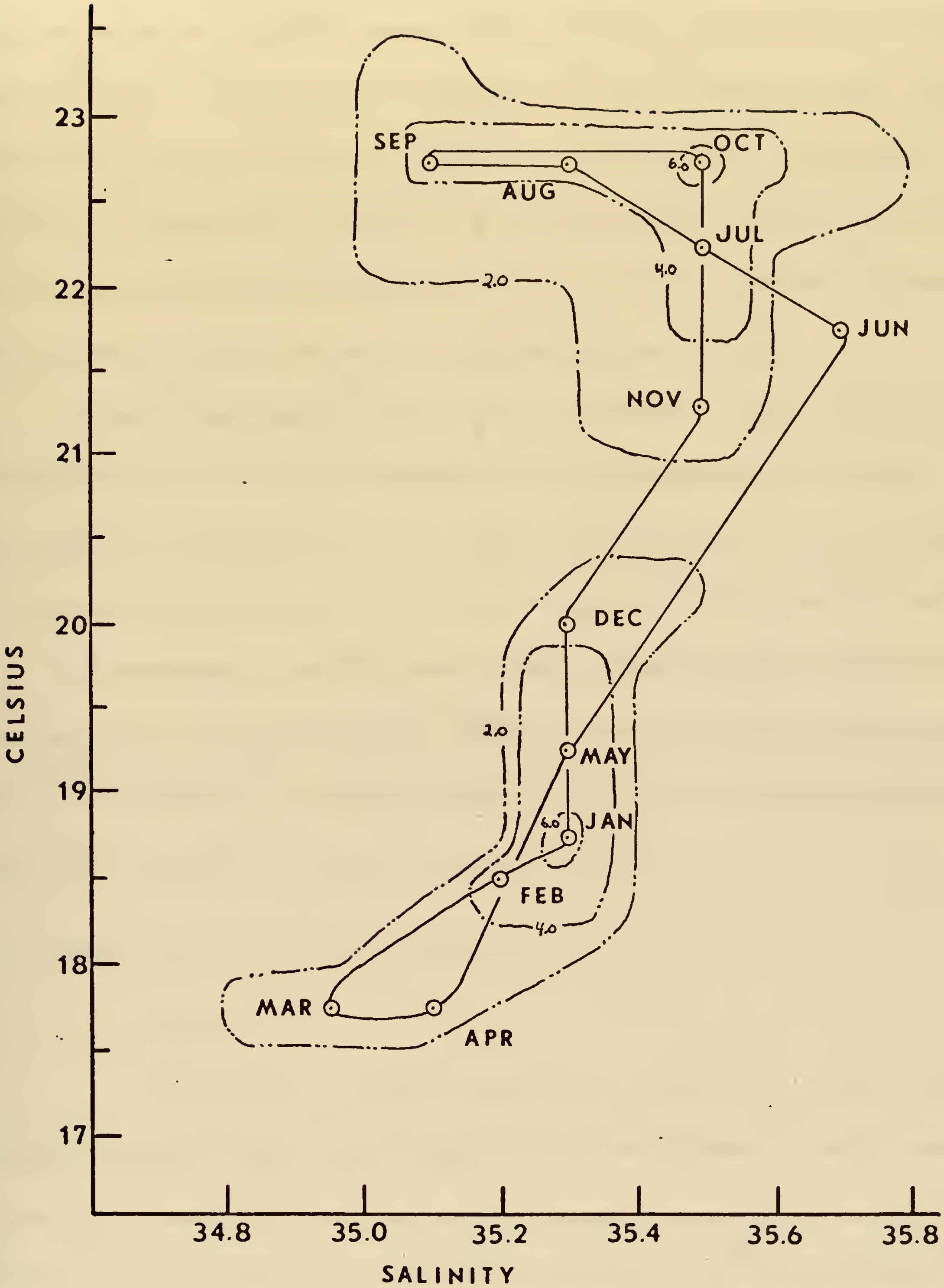

Figure 7. Monthly Temperature and Salinity Modal Points Resulting from the Bi-Variate Analysis of the Data, 1968 through 1970.

The following discussion will begin with a description of the fluctuation in the monthly means of temperature and salinity over the period January, 1968 through December, 1970. This description will be primarily deterministic in nature and will include an examination of surface temperature anomalies and incorporate Robinson's [1971] long-term monthly mean temperature data. Salinity anomalies cannot be determined due to the lack of long-term mean values.

Relationships between sea surface temperature and subsurface temperatures at 50 and 200 meters will then be examined utilizing correlation coefficients from the regression analysis. The correlation of surface temperatures with salinity will also be discussed in detail.

Fluctuations in surface water mass characteristics will not be discussed as a separate section. Annual water mass fluctuations can be easily followed by referring to the T-S diagram resulting from the bi-variate analysis mentioned earlier (Figure 7).

A. TEMPERATURE FLUCTUATIONS

1. Surface

The annual variation of surface temperature in any region is primarily a function of the radiation income, ocean currents, and prevailing winds. The average annual range between the mean winter (February) and summer (August) temperatures at 30° North latitude in the North Pacific Ocean is about 6° C [Sverdrup, et al, 1942].

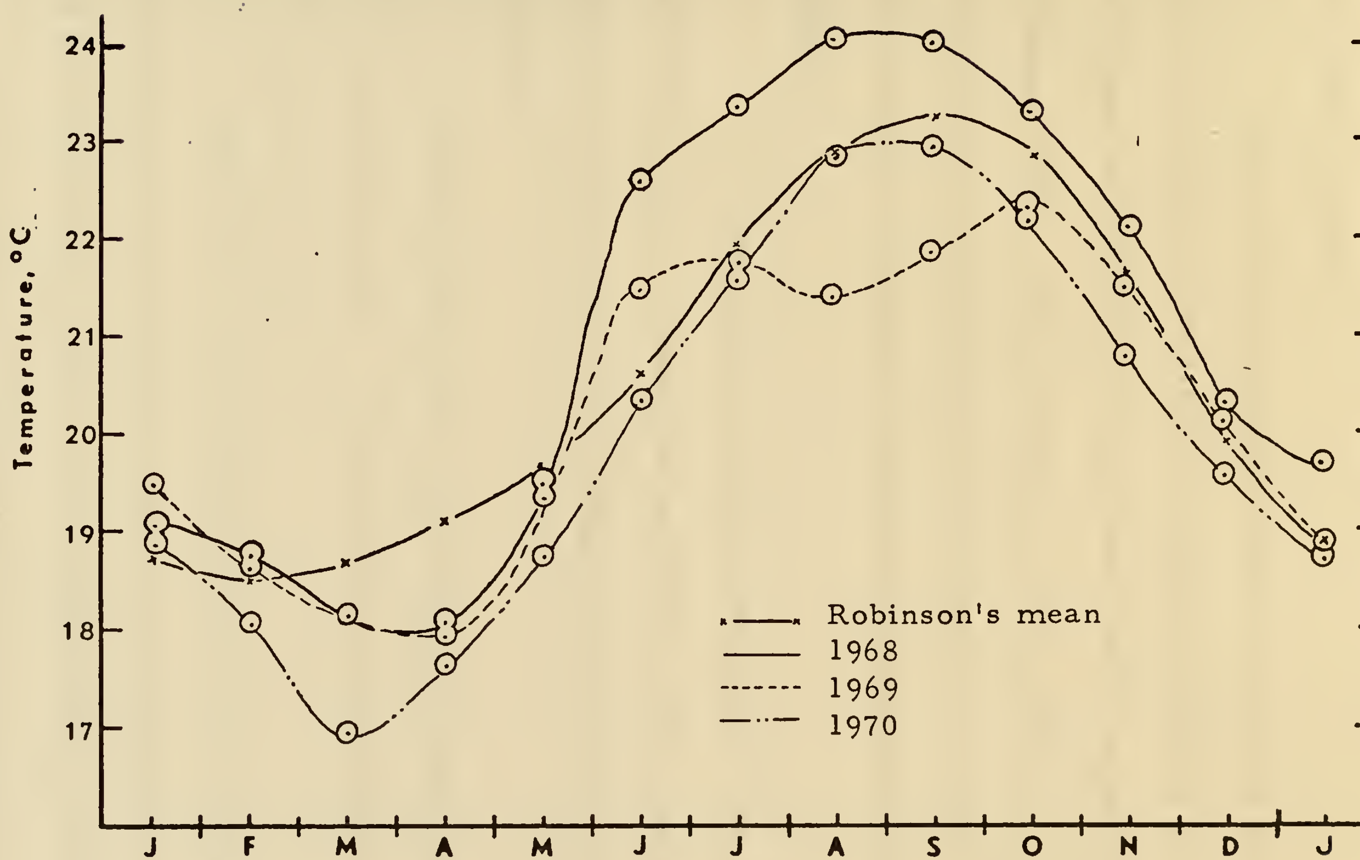

Figure 8. Monthly means of the Observed Surface Temperatures, 1968 through 1970 and Robinson's (1971) Long-term Monthly Means.

Dietrich [1957] and Sverdrup, et al, [1942] have attributed this annual fluctuation of temperature primarily to the annual periodicity of incoming solar radiation.

The calculated monthly means of observed surface temperature for the period 1968-1970 are plotted in Figure 8. Also shown in this figure are the 20-year long-term monthly mean values compiled by Robinson [1971]. From this figure it is possible to visualize the dominate features of the annual fluctuations in sea surface temperature and their deviations from the long-term mean during the period of interest.

The most pronounced feature observed is the marked annual cycle of the sea surface temperature. Each year is characterized by a distinct minimum and maximum in monthly mean temperature.

Surface temperatures exhibited an average annual range of 5.3° C during this period. The greatest range in temperature, about 6.0° C, occurred in 1968.

The shape of each monthly mean surface temperature curve is typical for the latitude under consideration as described by Isaacs [1969] except for short-term perturbations. He has indicated that the cycloidal character of the temperature curve is due to the differences in anisotropic heat flow resulting from fluctuating mixed layer depths. Annual variations in the depth of the mixed layer,

after Bathen [1972], at OWS November is shown in Figure 9. The resulting differences between the processes of shallow heating, i.e., the production of a shallow stable layer during the winter-to-summer transition, and deep cooling (with associated instability and mixing) during the late summer-to-winter transition and the winter periods is believed to account for the shape of the temperature curves at the surface.

Comparison of the calculated monthly means with Robinson's [1971] long-term mean reveals several apparent long-term and short-term deviations during the period of interest. The most obvious deviation is the consistently large difference between the long-term mean during the winter months of March and April. All three years were significantly (about 1° C) cooler during these months than the long-term mean. Beland [1971] noticed this recurring difference but did not elaborate on it.

It is interesting to hypothesize as to the cause of this recurring difference. There are four possible explanations: 1.) the advection of cold water into this region each year suggesting a recent change in the winter surface circulation pattern in the subtropic zone, 2.) a greater than normal loss of heat to the atmosphere in winter, 3.) recurring seasonal reductions in the amount of incoming solar radiation due to increased cloud cover, or, and most unlikely, 4.) an error in the long-term mean.

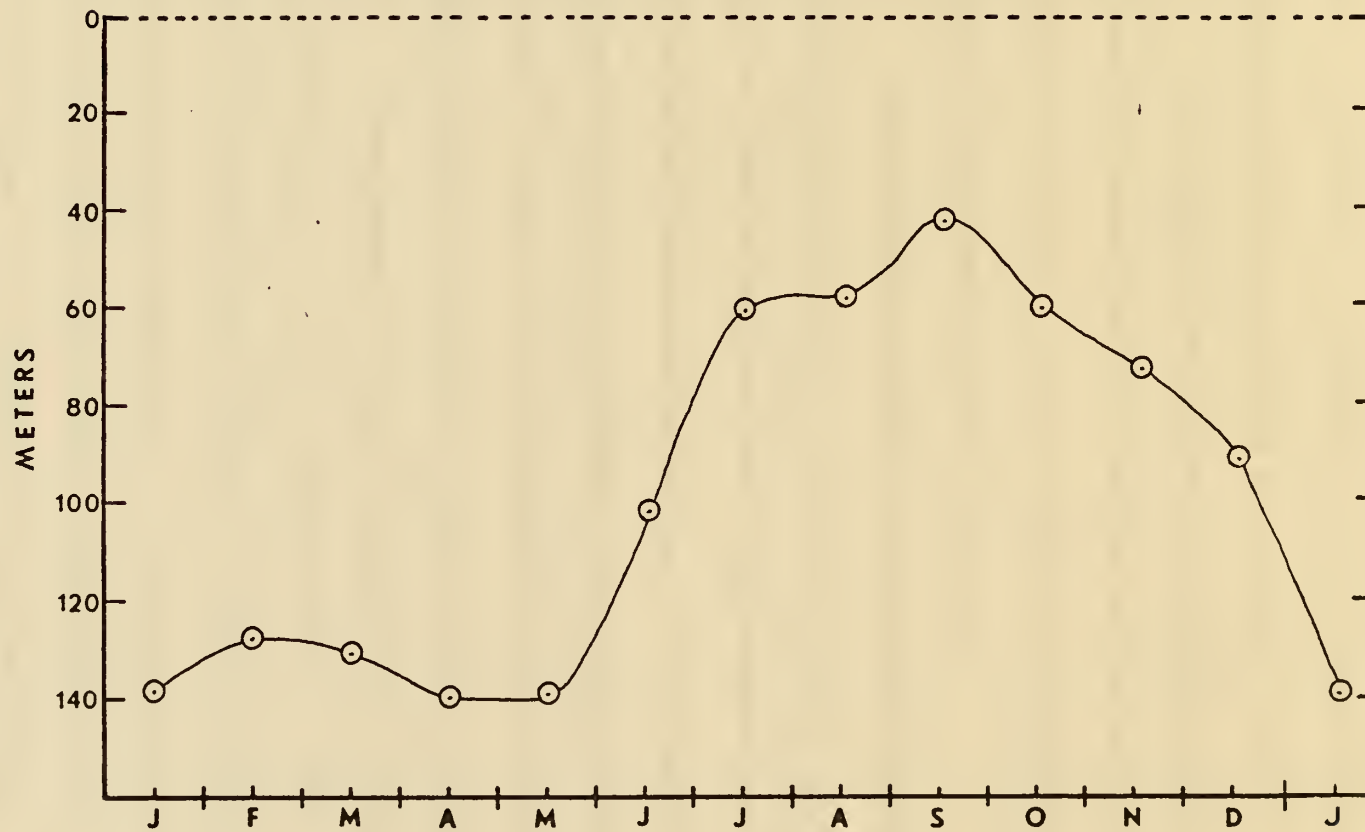

Figure 9. Annual Variations in the Mixed Layer Depth at 30° North, 140° West (after Bathen, 1972).

The remaining months in each year conform more closely with the long-term mean except for apparent individual year-to-year anomalous conditions. A compilation of the monthly magnitudes of the surface temperature anomalies is presented in Table 1.

It is apparent that 1968 was anomalously cold during the winter months of March and April and was anomalously warm during the remainder of the year. Surface temperatures gradually approached the long-term mean toward the end of the year.

As previously mentioned, Namias [1971] noted the occurrence of anomalously warm water during the summer of 1968. He attributed one-third of the anomalously high temperature to bulk heating (exclusive of advection and mixing). The remainder apparently resulted from the inward advection and downwelling of insolation heated surface water. Beland [1971] also studied this pool of warm water and determined that it extended to a depth of about 122 meters.

From January to June the shape of the 1969 monthly mean temperature curve closely resembles that for 1968. During June and July the temperature appears to remain nearly constant and then decreases by approximately 0.3° C during August. Surface temperatures are then observed to increase until October, after which temperatures appear to decrease in the expected fashion.

The abnormal decrease in surface temperature during the summer of 1969 may have been a result of any one of several

TABLE I. Surface Temperature Anomalies at OWS November, Based on Robinson's [1971] 20-year Long-term Mean, 1968 through 1970.

	Robinson Long-term Mean	1968 Monthly Mean	1968 Anomaly	1969 Mean	1969 Anomaly	1970 Mean	1970 Anomaly
J	18.8	19.0	0.2	19.5	0.7	18.9	0.1
F	18.6	18.7	0.1	18.6	0.0	18.0	-0.6
M	18.7	18.2	-0.5	18.1	-0.6	16.9	-1.8
A	19.1	18.1	-1.0	18.0	-1.1	17.6	-1.5
M	19.6	19.5	-0.1	19.3	-0.3	18.8	-0.8
J	20.6	22.6	2.0	21.5	0.9	20.4	-0.2
J	21.8	23.4	1.6	21.8	0.0	21.6	-0.2
A	22.8	24.1	1.3	21.4	-0.6	22.9	0.1
S	23.2	24.1	0.9	21.9	-1.3	23.0	-0.2
O	22.8	23.3	0.5	22.4	-0.4	22.4	-0.4
N	21.5	22.2	0.7	21.5	0.0	20.8	-0.7
D	19.9	20.3	0.4	20.2	0.3	19.6	-0.3

environmental factors. The introduction of colder, modified subarctic water by advection, decreased insolation caused by a heavy cloud cover, or mechanical or convective mixing in the upper layers of the mixed layer are three possible explanations.

The hypothesis is advanced that this cooling of surface water was due to the transport of modified subarctic water into this region causing the southern boundary of the transition zone to move equatorward [Roden, 1970].

From the meridional transport data of Wickett and Thomson [1970] presented in Figure 5, it can be seen that a relatively large volume of cooler water was transported equatorward between longitudes 135° and 145° West at 30° North during April through July. This transport may account for the significant reduction in temperatures noted. Further evidence for this influx is provided by an examination of water column stability.

During this period of time stability between the surface and the 50 meter level decreased significantly. This can be seen in Figure 10. Whereas during 1968 and 1970 stability steadily increased until August, in 1969 it suddenly decreased during July and August. However, stability did not decrease to a point where convective mixing, resulting in a temperature decline, could easily occur. This is further support for the hypothesis that subarctic water was advected into this region.

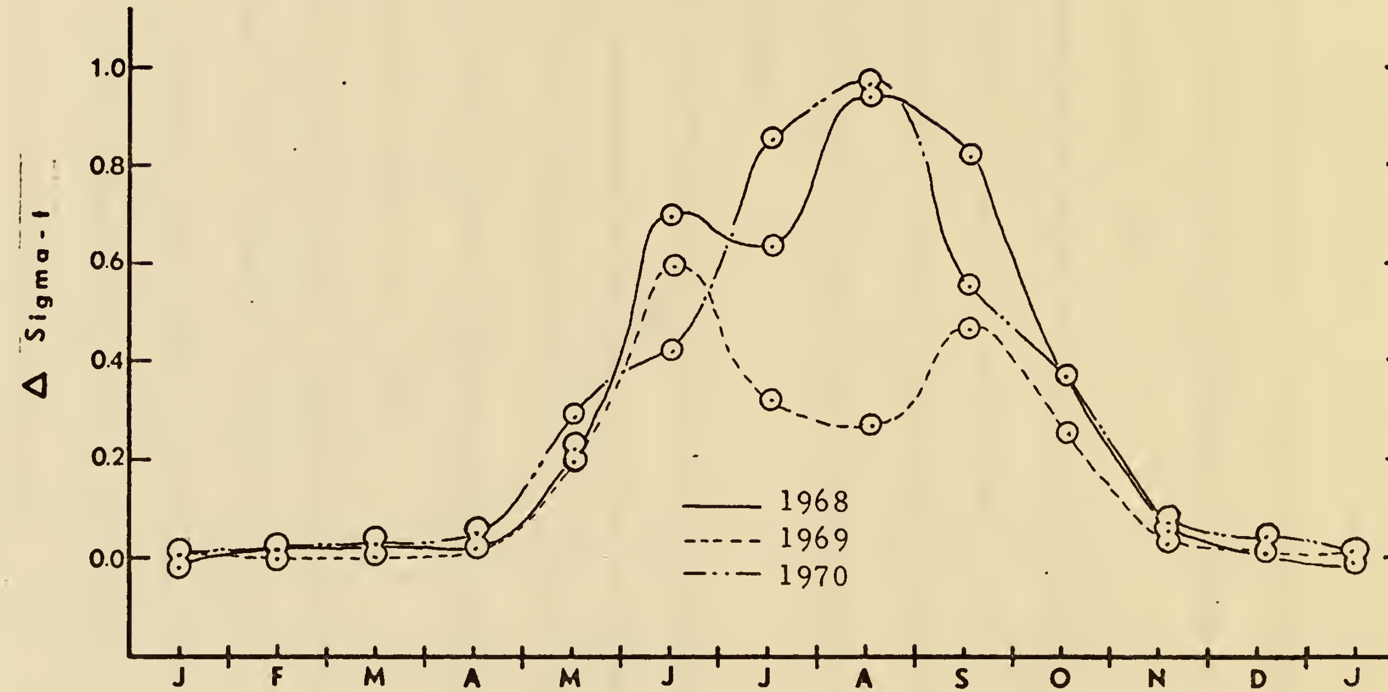

Figure 10. Variations in Monthly Mean Stability as Indicated by the Difference Between σ_{50} and σ_{sfc}.

The following year, 1970, was the most conformal with respect to Robinson's [1971] long-term mean with the exception that temperatures were somewhat lower than the long-term mean. However, the only significant cold water anomaly was observed during the previously mentioned winter perturbation. In general, 1970 was a cooler year than 1968 or 1969.

Temperatures appeared to be changing most rapidly during the transitional winter-to-summer heating phase. The greatest rate of change of temperature occurred in May (Figure 8). This trend is also reflected in the higher monthly standard deviations (Table 2).

2. <u>50 Meters</u>

Below the surface variations of temperature depend on four factors: (1) variations in the amount of heat absorbed at different depths, (2) the effect of heat conduction, (3) variation in the currents related to lateral displacements of water masses, and (4) the effect of vertical motion [Sverdrup, et al, 1942].

A plot of mean monthly temperatures observed at 50 meters during 1968 through 1970 is shown in Figure 11. Since long-term means were not available at this depth, it will be possible to discuss only each yearly curve relative to the other two. However, a useful indication of temperature patterns can be seen.

The prominent feature of these curves is, as was discussed with respect to the surface temperatures, the distinct annual cycle.

TABLE II. Monthly Standard Deviations of Surface Temperature Calculated for the Years 1968 through 1970, in Degrees Celsius.

	1968	1969	1970
JAN	0.05	0.08	0.10
FEB	0.06	0.07	0.21
MAR	0.03	0.00	0.03
APR	0.06	0.07	0.15
MAY	0.30	0.31	0.05
JUN	0.01	0.13	0.03
JUL	0.03	0.01	0.29
AUG	0.01	0.02	0.05
SEP	0.11	0.02	0.04
OCT	0.08	0.04	0.13
NOV	0.08	0.13	0.07
DEC	0.08	0.15	0.19

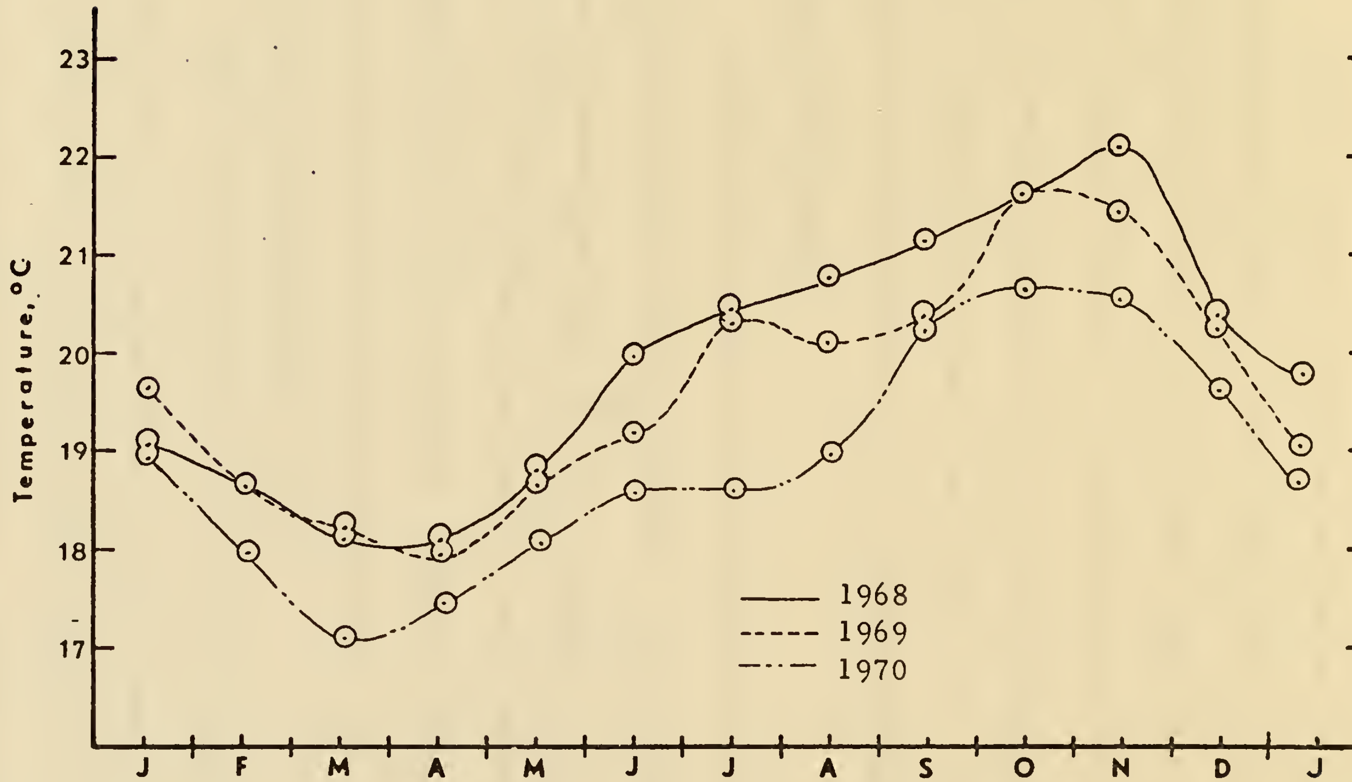

Figure 11. Monthly Means of Observed Temperatures at 50 Meters, 1968 through 1970.

It is apparent that there is a single yearly temperature minimum (during March or April) and a maximum (during October or November).

Another feature of the 50 meter temperature curves is that the slope of the warming phase of each curve is less than that of the corresponding portion of the surface curves. Apparently the rate of temperature increase is slower at 50 meters than at the surface. This is vividly illustrated by comparing daily mean temperature plots of the data at the surface and 50 meter level (Figure 12). From this figure it can be seen that both curves are essentially identical except between May and November.

In 1968 monthly mean temperatures at 50 meters were lowest during the months of March and April. The minimum mean temperature observed was about 18.1° C. Temperatures then appeared to increase, more slowly than at the surface, until November when a mean maximum of 22.1° C was reached. After November temperatures rapidly decreased until April of the following year. The range of temperature in 1968 was approximately 4.0° C.

After the minimum of about 17.9° C was reached in April of 1969, temperatures increased rather rapidly. However, the trend of increasing temperatures was interrupted in August when temperatures were observed to temporarily decrease. This decrease was previously noted to occur at the surface. The temporary depression of temperature persisted through the following month and is probably due to a delay in the conduction of heat from the surface to 50 meters.

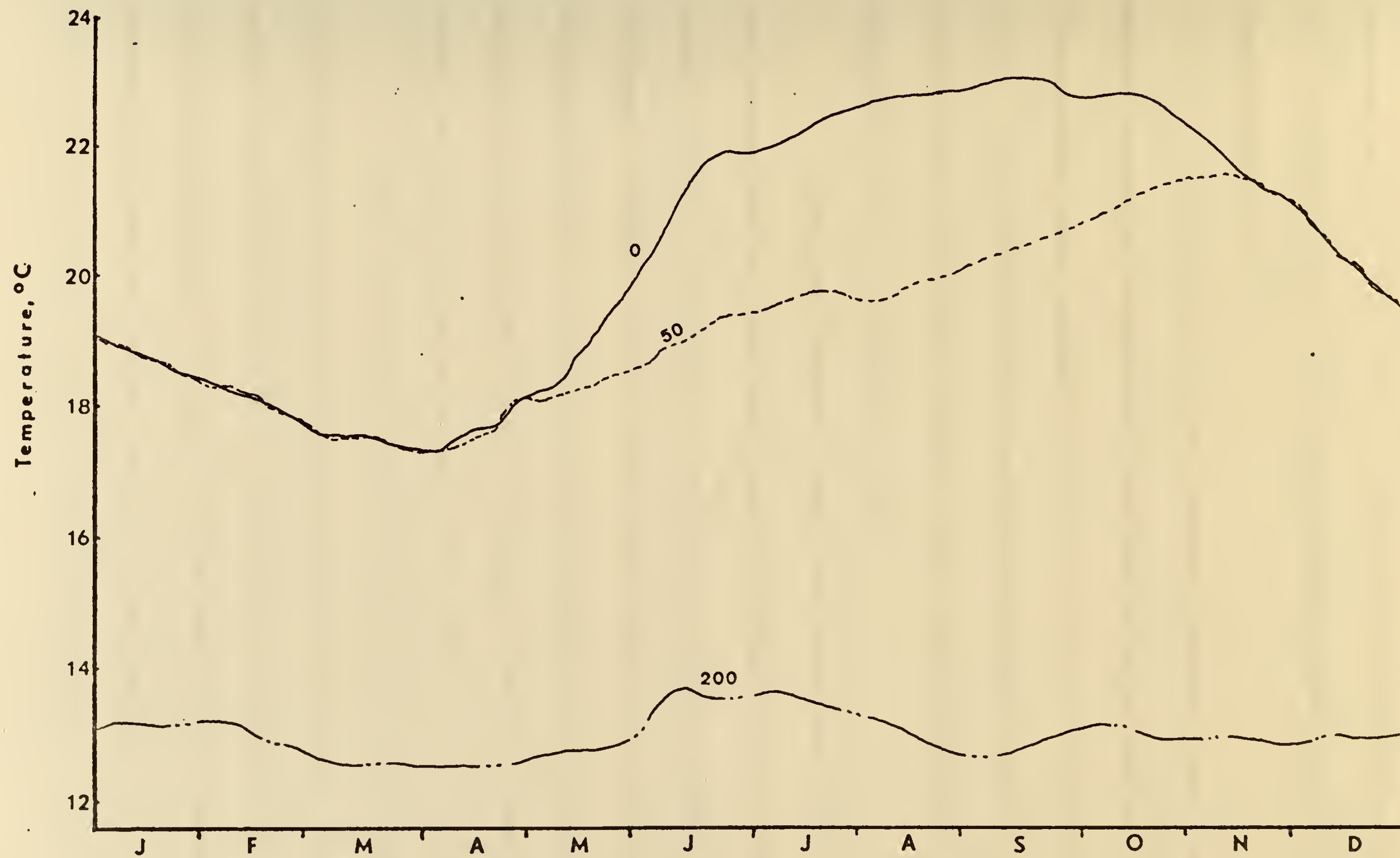

Figure 12. Surface, 50 and 200 Meter Average (Daily) Year Temperatures computed from the Data, 1968 through 1970.

Temperatures warmed again after September reaching a maximum of 21.7° C in October, followed by decreasing temperatures until the following year. The range of temperature during 1969 was approximately 3.8° C.

As at the surface mean monthly temperatures observed in 1970 were significantly lower than those of the preceding two years. The minimum mean temperature of about 17.0° C was observed in March. Temperatures then increased until October when the maximum of only 20.6° C was reached. The range in temperatures was approximately 3.6° C during this year.

Comparing Figures 8 and 11 and examining Figure 12 it can be seen that the winter minimum at 50 meters occurs simultaneously with that at the surface. Referring to Figure 9 which relates the yearly fluctuations in the depth of the mixed layer as compiled by Bathen [1972], it can be seen that during this period the water column is isothermal well below 50 meters. Therefore, one would expect the simultaneous occurrence of the temperature minimum.

Due to the thermal stratification of the water column resulting from the formation of the seasonal thermocline, the exchange of heat from the surface to 50 meters is limited to the process of thermal conductivity. However, in the absence of a seasonal thermocline, heat may be exchanged by a combination of convective mixing, mechanical mixing and thermal conductivity. A net result

TABLE III. Month of Occurrence and Range Between Mean Monthly Minimum and Mean Monthly Maximum Temperature at the Surface and 50 Meters, 1968 through 1970.**

		Surface		50 Meter		Lag direction
		Month	Range	Month	Range	and magnitude
1968	Min	APR		MAR/APR		0
			6.0		4.0	
	Max	AUG		NOV		+3
			6.1		4.2	
1969	Min	APR		APR		0
			4.4		3.8	
	Max	OCT		OCT		0
			5.4		4.6	
1970	Min	MAR		MAR		0
			6.0		3.6	
	Max	SEP		OCT		+1

** In column 7 "+" means surface leads 50 meters, magnitude in months.

of thermal stratification is a restriction in the flow of heat from the surface to the 50 meter depth.

This restriction in the flow of heat is indicated by the delay in the occurrence of the maximum monthly mean temperature at 50 meters relative to the surface. In 1968 the surface maximum occurred in August and the 50 meter maximum was delayed until November, a difference of two months. In 1969 the surface and 50 meter maximum temperatures occurred simultaneously in October, a possible reflection of the abnormal mid-summer cooling discussed earlier. During 1970 a one month delay between maximum temperatures (September and October) was observed. It is apparent that thermal stratification, unless reduced by abnormal cooling, may result in a one to two month delay in reaching the maximum temperature at 50 meters.

Differences between the annual range of temperatures and the occurrence of temperature extremes (maximum and minimum) at the surface and 50 meters are presented in Table 3. From this table it can be readily seen that all winter mean temperature minima occurred (with the exception of 1969) one to three months earlier at the surface, and the range of mean temperatures decreases by approximately 1.3 ^{o}C at 50 meters compared with the temperature range at the surface.

TABLE IV. Monthly Standard Deviations of 50 Meter Temperature Calculated for the Years 1968 through 1970, in Degrees Celsius.

	1968	1969	1970
JAN	0.05	0.09	0.12
FEB	0.13	0.07	0.19
MAR	0.01	0.00	0.05
APR	0.05	0.07	0.18
MAY	0.11	0.15	0.12
JUN	0.11	0.20	0.06
JUL	0.03	0.01	0.05
AUG	0.10	0.18	0.05
SEP	0.24	0.05	0.10
OCT	0.07	0.15	0.03
NOV	0.07	0.11	0.06
DEC	0.08	0.19	0.18

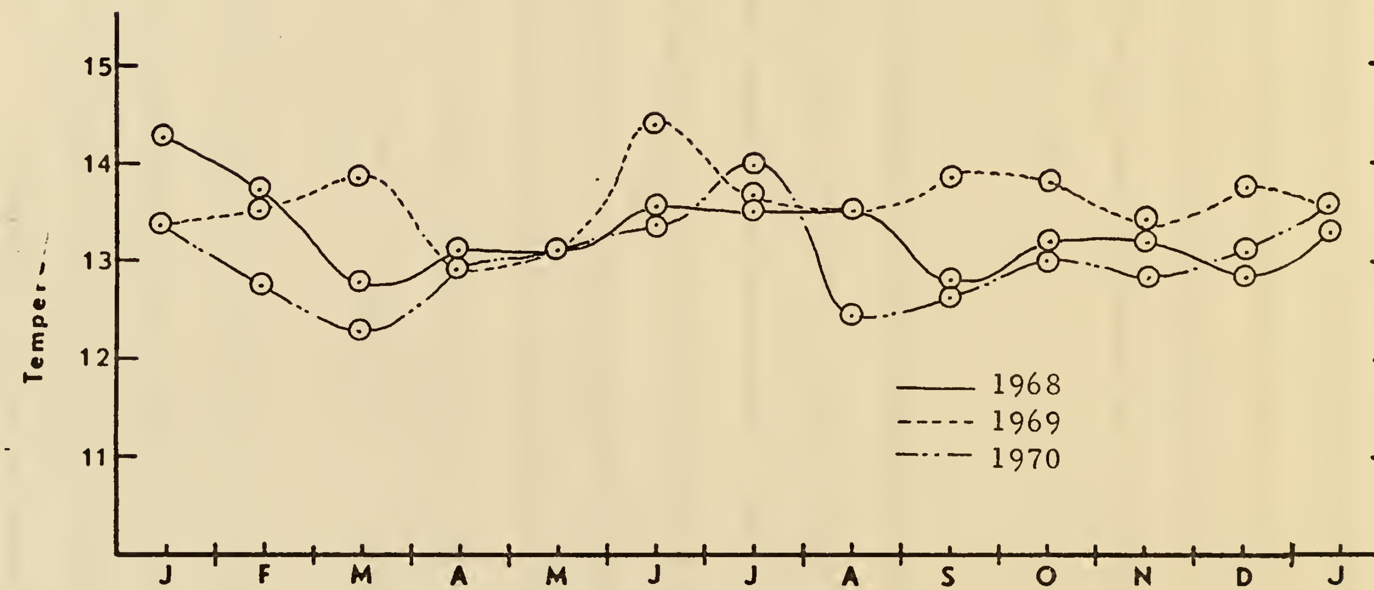

Figure 13. Monthly Means of Observed Temperatures at 200 Meters, 1968 through 1970.

Monthly standard deviations of temperature at 50 meters were generally smaller than those at the surface (Table 4). During 1968 and 1969 the larger standard deviations occurred during the months of the winter-to-summer transitional period (as they did at the surface). In 1970 several larger standard deviations occurred throughout the year indicating more variations occurring this year than during the previous two years.

3. <u>200 Meters</u>

Temperature variations at 200 meters are, in contrast to those in the upper layers, much reduced in range and show little annual periodicity. Mean monthly temperatures are shown in Figure 13. A power spectrum analysis, employing a fast Fourier transform of questionable reliability due to the presence of large low frequency components and a relatively short record length for such an analysis, indicates that most of the energy is centered in the component with a period of approximately 1.5 years. Temperatures appear to center around a mean of 13.3° C.

The generalized behavior of temperature at 200 meters is perhaps best shown using the average (daily) year plot (Figure 12). This figure shows a slight seasonal cooling trend in temperature during January and February, followed by a slow increase through June. Then another cooling period follows and lasts through August after which temperatures very slowly increase until December or early January.

Husby [1969] indicated that slightly higher temperatures at 200 meters noted during 1968 resulted from convective mixing that occurs during this period of time at the surface due to the erosion of the seasonal thermocline and continued surface cooling. This trend was also noted in the plot of the computed average (daily) year. If this were the general case, both increases in temperature and high negative correlations with surface temperature during this phase of the temperature cycle would be noted to occur annually. The correlation between the surface and 200 meters during January and February of 1968 were found to be relatively high (0.67) and positive. However, as shall be discussed in a later section, low correlations were calculated during the other three cooling and winter phases of annual temperature cycles. This indicates that generally there is no correlation between the surface temperatures and temperatures at these depths during periods of convective mixing.

B. SALINITY FLUCTUATIONS

1. Surface

As mentioned earlier, the lack of long-term mean values precluded the determination of salinity anomalies. However, an examination of mean monthly salinities computed over the period 1968 through 1970 reveals several interesting features in the annual fluctuation of surface salinity. Monthly surface salinity means are presented in Figure 14.

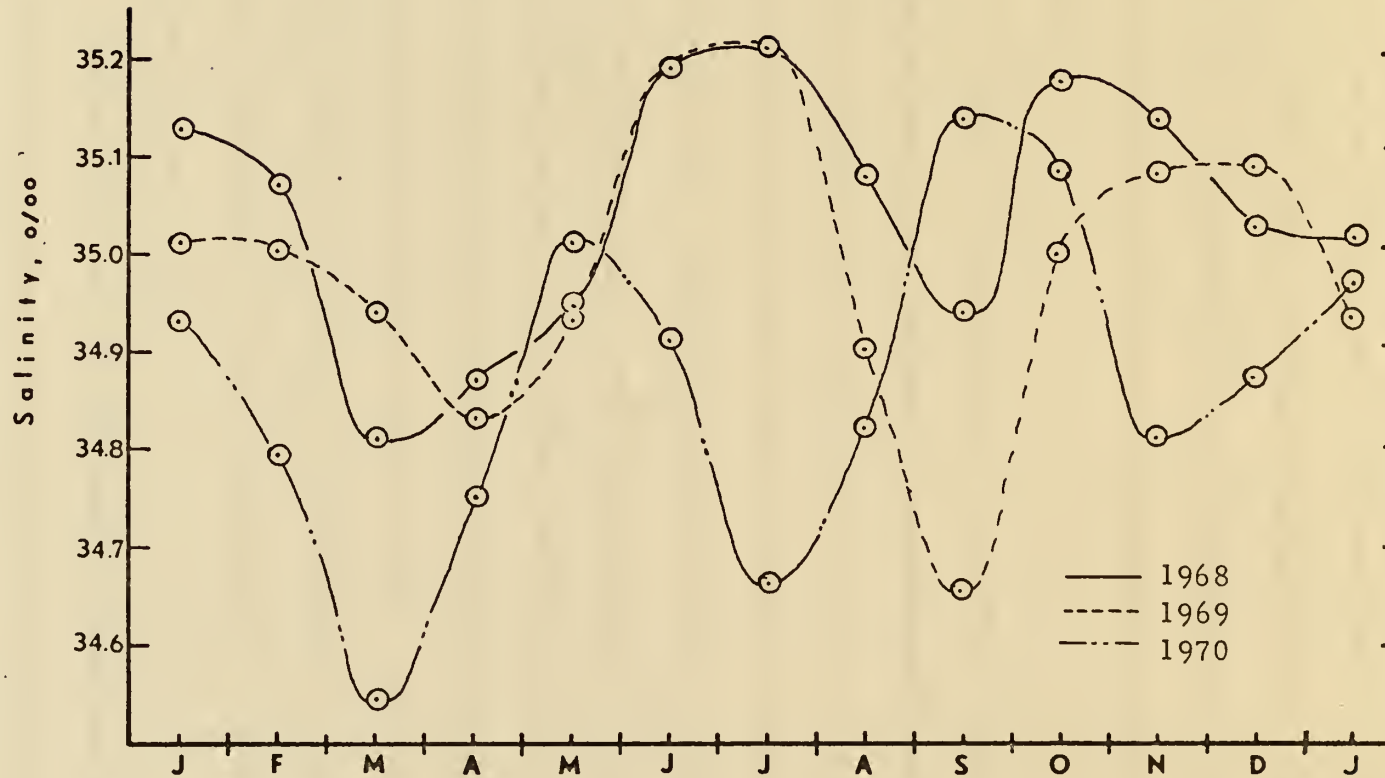

Figure 14. Monthly Means of Observed Surface Salinity, 1968 through 1970.

It is apparent that there is a semi-annual periodicity in the salinity cycle at this station. A salinity minimum occurred during either March (1970) or April (1968 and 1969). In 1968 this mean minimum was about 34.9 ‰ while in 1968 the minimum was about 34.8 ‰. The following year, 1970, apparently witnessed a significant reduction in the surface salinity with the mean being only 34.5 ‰.

This significant decrease in the mean salinity noted in 1970 may be related to the presence of an abnormally cold water mass in this area. It appears that a large mass of cool, fresh subarctic water from the north was advected into this region (Figure 5) during April and May of 1970. Due to the inherent errors of lag time in the calculations introduced by the assumption to ignore the inertia of the surface transport system, it is feasible that this persistent and significant amount of transport might well account for the depressed mean temperatures and salinities noted in 1970. The occurrence of such periodic advections of norther water amounts to a north-south displacement of the transition zone between subarctic and subtropical water masses [Roden, 1970].

During 1968 and 1969 following the first minimum the salinity continued to increase until a maximum occurred in July. For both years the range of salinity between these extrema was a little over 0.3 ‰. The maximum in 1970 occurred in May two

months earlier than in the previous years, the range in salinity being 0.4 ^{o}/oo.

Following these maxima, salinities decreased rapidly in both 1968 and 1969 until September when the second minimum occurred. The decrease in salinity in 1969 was considerably greater than in 1968 (greater than 0.2 ^{o}/oo). The second minimum in 1970 occurred in July, again two months earlier than in 1968 or 1969. After this second minimum salinity increased until October in 1968 (with an increase in salinity of 0.3 ^{o}/oo over the minimum) and December in 1969 (with an increase of 0.4 ^{o}/oo).

In 1970 the second maximum was reached in September and had a range of approximately 0.5 ^{o}/oo. Afterward salinity decreased until a third minimum occurred in November. A range in the monthly mean values of approximately 0.4 ^{o}/oo was observed. It is interesting to note that the successive minimum and maximum values increased at each occurrence, thereby indicating an overall increase in salinity during the entire year of of 1970. This is an apparent indication of the re-establishment of the normal salinity condition superimposed over fluctuations caused by forces resulting in the occurrence of periodic maximum and minimum.

2. <u>50 Meters</u>

The fluctuations in salinity at 50 meters appears to be very similar to that at the surface. The monthly mean values during

the period of interest are shown in Figure 15. There are some differences, however. These differences are most readily evident from Table 5 which summarizes the range in salinity between maximum and minimum extremes and the time of occurrence of these extremes at both the surface and 50 meters.

The range in salinity is generally less at 50 meters (by about 0.11 $^{o}/oo$) than at the surface. This is also the case with temperatures as previously indicated. From the data presented in Table 5 it is nearly impossible to draw conclusions regarding possible time lags between the occurrence of salinity extremes at the surface and 50 meters. It seems that surface salinity led 50 meter salinities by one month three times, lagged by one month five times and there were no time differences five times. However, note that the occurrence or non-occurrence of time leads or lags appear to be grouped according to direction, indicating a possible common connecting relationship.

3. <u>200 Meters</u>

Salinity variations at 200 meters differ markedly from those in the surface layers in both range and periodicity. Figure 16 is a plot of the monthly means of the observed salinity values measured at 200 meters, 1968 through 1970. The overall mean of all observed values is 34.2 $^{o}/oo$.

The range of salinity during the period of interest was small. The mean minimum was about 34.03 $^{o}/oo$ while the maximum

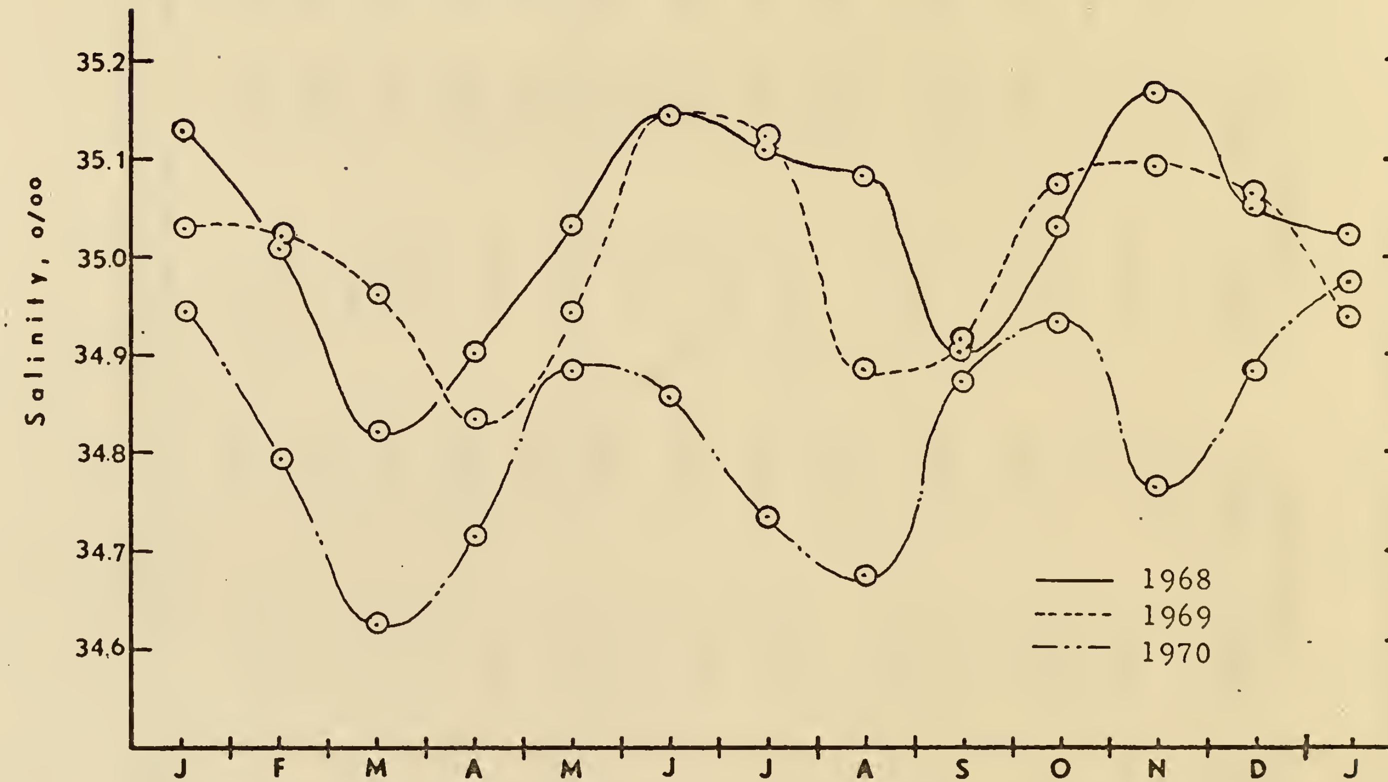

Figure 15. Monthly Means of Observed 50 Meter Salinity, 1968 through 1970.

TABLE V. Month of Occurrence and Range Between Mean Monthly and Mean Monthly Maximum Salinity Means at the Surface and 50 Meters, 1968 through 1970.**

		Surface		50-meters		Lag direction
Year		Month	Range	Month	Range	and Magnitude
1968	Min	APR		MAR		-1
			0.34		0.32	
	Max	JUL		JUN		-1
			0.27		0.24	
	Min	SEP		SEP		0
			0.24		0.27	
	Max	OCT		NOV		+1
			0.25		0.34	
1969	Min	APR		APR		0
			0.38		0.31	
	Max	JUL		JUN		-1
			0.56		0.26	
	Min	SEP		AUG		-1
			0.44		0.21	
	Max	DEC		NOV		-1
			0.54		0.47	
1970	Min	MAR		MAR		0
			0.46		0.26	
	Max	MAY		MAY		0
			0.35		0.21	
	Min	JUL		AUG		+1
			0.48		0.26	
	Max	SEP		OCT		+1
			0.33		0.17	
	Min	NOV		NOV		0

** In column 7 "+" means surface leads 50 meters, "-" means surface lags 50 meters, magnitude in months.

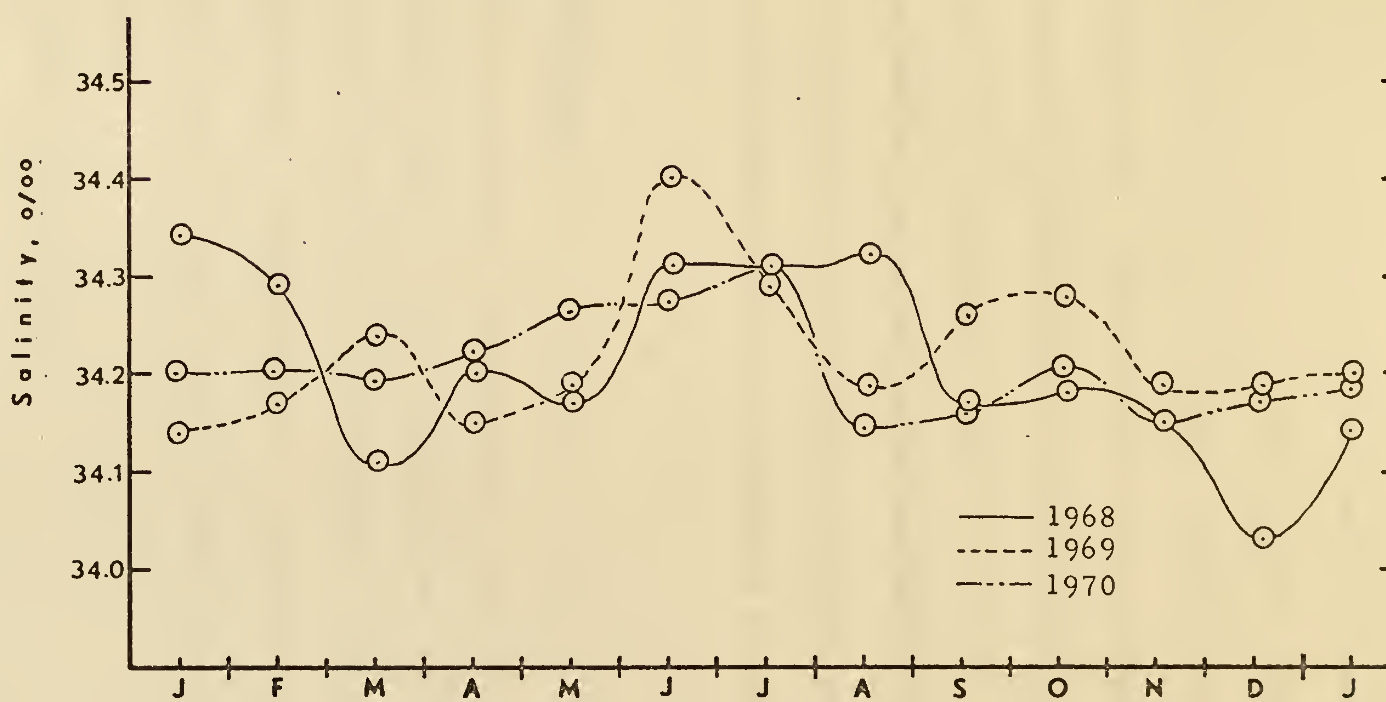

Figure 16. Monthly Means of Observed 200 Meter Salinity, 1968 through 1970.

was 34.40 $^{o}/oo$, the difference between the extreme means being approximately 0.4 $^{o}/oo$.

Results of a power spectrum analysis, again using a fast Fourier transform, indicates most of the energy is contained in that component with a period of 1.5 years, as was the temperature fluctuations at this depth. This does not necessarily imply that the fluctuation of these two parameters are caused by the same forcing processes. An overall correlation coefficient calculated between 200 meter temperature and salinity values was found to be only 0.23. This indicates that there is no significant correlation between these parameters at 200 meters or that each fluctuates independently of the other.

C. CORRELATIONS

Correlation coefficients from the linear regression analysis are summarized in Table 6. Each coefficient was calculated with surface temperature as the dependent variable. Each year was separated into winter, winter-to-summer, summer and summer-to-winter segments based on surface temperatures and an analysis run on each segment.

1. Temperatures

1. <u>50 Meter Temperatures</u>

Temperatures observed at 50 meters are well correlated to surface temperatures during the transition periods. However,

TABLE VI. Correlation Coefficients, by Season, Resulting from a Linear Regression Analysis of Surface Temperature, Surface Salinity, and 50 Meter Temperature Data, 1968 through 1970.

	1968		1969		1970		Mean	
	Sfc Sal	50 m Temp	Sfc Sal	50 m Temp	Sfc Sal	50 m Temp	Sfc Sal	50 m Temp
Winter	0.61	0.58	0.61	0.56	0.77	0.42	0.66	0.52
Warming	0.59	0.90	0.77	0.70	-0.11	0.67	0.42	0.75
Summer	-0.28	0.31	0.16	0.40	-0.05	-0.29	-0.05	0.14
Cooling	0.57	0.88	0.84	0.98	-0.01	0.96	0.47	0.94

they are poorly correlated during both the summer and winter phases of the annual temperature cycle.

The lowest correlations occurred during summer periods. Referring to Figures 3 and 4 it can be seen that during the summer period, surface temperatures are nearly constant at the annual maximum while temperatures at the 50 meter level are still increasing due to the time delay discussed in an earlier section of this thesis.

The mean correlation for the winter periods was about 0.52. This indicates no significant correlations occurred during the winter periods. It is hypothesized that this is due to the short-term response of surface temperature to atmospheric influences. These influences are not of sufficient length in time to be transmitted to 50 meters.

The highest correlations occurred during the transition periods. Correlations were somewhat variable during the winter-to-summer transition, having an average of 0.75 over the three years. The warming period during 1968 had a high correlation coefficient of 0.90 and the other two years had a coefficient of approximately 0.70.

Higher correlations during the warming transition period are a result of the simultaneous increase in temperatures at both the surface and at 50 meters. From Figures 8 and 11 it can be seen that, initially, the two temperatures increase concurrently. However,

after a short period of time, the formation of the seasonal thermocline occurs resulting in the construction of an effective barrier to the flux of heat between the surface and lower depths. This would suggest a positive weak correlation between the two depths with respect to temperature.

Significant correlations between surface and 50 meter temperatures were found to occur during the summer-to-winter temperature transition period. The mean correlation for the three years was 0.94, with the highest correlation (0.98) occurring in 1969. It is during this time period that the seasonal thermocline is eroded away and the barrier to the flux of heat between the surface and the 50 meter level is removed. Furthermore, cooling of the surface waters results in convective mixing resulting in almost simultaneous changes in temperature throughout the mixed layer. It is most likely this latter process that causes the correlation coefficient to be so high.

2. <u>200 Meter Temperatures</u>

There appears to be little correlation between surface and 200 meter temperatures except during the warming phase of the surface temperature cycle. Seasonal correlation coefficients are shown in Table 7. A mean correlation coefficient of 0.63 was computed for the winter-to-summer warming transition. This coefficient is not indicative of a high correlation during this period of time, but

TABLE VII. Seasonal Correlations Between Surface and 200 Meter Temperatures, 1968 through 1970.

	1968	1969	1970	Mean
Winter	-0.26	-0.04	0.38	0.03
Warming	0.71	0.63	0.55	0.63
Summer	-0.26	0.37	-0.24	-0.04
Cooling	-0.41	0.51	-0.27	-0.06

it has possible significance when compared to the extremely low coefficients computed for the other seasons.

3. Surface Salinity

It is apparent that surface salinity in general is not well correlated with surface temperature. This is true during each of the four yearly phases of the annual temperature cycle. The highest correlation, averaged over the three years of interest, occurred during the winter. The lowest correlation occurred during the summer.

During the summer-to-winter transition period of 1969/1970 a relatively high correlation of 0.84 was computed. Interestingly, this is the period during which surface temperatures and salinities were decreasing, resulting in the abnormally low temperatures and salinities observed during the whole of 1970. Apparently this high correlation is a result of the simultaneously changing temperatures and salinities brought about by the influx of subarctic water.

IV. CONCLUSIONS AND RECOMMENDATIONS

This study was involved with the description of short- and long-term fluctuations of concurrent temperature and salinity observations taken at the surface, within the mixed layer, and within the upper portion of the permanent thermocline at Ocean Weather Station November during the years 1968 through 1970.

The results of this research show that:

1. Surface temperatures had an annual periodicity with a mean range of approximately 5.6^{o} C. Comparison of the data with Robinson's long-term means reveals that there is great variability in year-to-year mean temperature curves. It was observed that anomalous decreases in temperature were often accompanied by decreases in salinity.

2. Temperature maximums at 50 meters were found to lag surface temperatures by one to three months. This lag is probably caused by thermal stratification resulting from the formation of the seasonal thermocline. Temperatures at both levels became nearly identical when the seasonal thermocline was eroded away during the summer-to-winter phase of the surface temperature cycle. It was also found that the annual range in temperature at 50 meters was only about 3.8^{o} C.

3. Salinity at both the surface and 50 meters has a semi-annual periodicity. No satisfactory conclusion was drawn as to what causes this periodicity. Possibly periodic advection of low-salinity subarctic water into this region occurs.

4. Surface temperature appears to be highly correlated with 50 meter temperatures only during the surface temperature transitional periods. The highest correlation occurred during the summer-to-winter transition period.

5. There appears to be little correlation of surface temperature with temperatures at 200 meters. Temperature at 200 meters show only slight annual periodicity, as does salinity at this level.

6. Salinity appears to be, in general, poorly correlated with surface temperature. A single high correlation coefficient was calculated during an anomalous cooling trend that occurred during the summer-to-winter transitional period of 1969.

This study revealed completely unexpected and unexplained semi-annual variations in salinity. A further study of the fluctuations in salinity should be undertaken in order that the cause of this feature be found. Such an undertaking is, however, an extremely expensive proposition involving a tremendous investment in oceanographic research time. Recently the decision was made to discontinue two Ocean Weather Stations, including November. This will make future research even more difficult.

It is further recommended that this study be used as a basis for the study of the correlation between fluctuations of metereorologic factors and ocean surface temperature and salinity fluctuations. Perhaps such a study would shed more light on the causes of the observed oceanographic fluctuations noted during the course of this research.

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DOCUMENT CONTROL DATA - R & D

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1. ORIGINATING ACTIVITY (Corporate author) Naval Postgraduate School Monterey, California 93940	2a. REPORT SECURITY CLASSIFICATION Unclassified 2b. GROUP	
3. REPORT TITLE A Study of Surface, 50 Meter and 200 Meter Temperature and Salinity Fluctuations at Ocean Weather Station November, 1968-1970		
4. DESCRIPTIVE NOTES (Type of report and, inclusive dates) Master's Thesis; June 1973		
5. AUTHOR(S) (First name, middle initial, last name) Donnel E. Hansen		
6. REPORT DATE June 1973	7a. TOTAL NO. OF PAGES 75	7b. NO. OF REFS 20
8a. CONTRACT OR GRANT NO. b. PROJECT NO. c. d.	9a. ORIGINATOR'S REPORT NUMBER(S) 9b. OTHER REPORT NO(S) (Any other numbers that may be assigned this report)	
10. DISTRIBUTION STATEMENT Approved for public release; distribution unlimited.		
11. SUPPLEMENTARY NOTES	12. SPONSORING MILITARY ACTIVITY Naval Postgraduate School Monterey, California 93940	

13. ABSTRACT

Long and short-term surface, 50 and 200 meter temperature and salinity fluctuations at Ocean Weather Station November during 1968 through 1970 were examined using several statistical techniques. One technique, a unique monthly bi-variate modal analysis of surface temperature and salinity, proved to be a valuable research tool in that the resulting monthly modal cells, when plotted on a T-S diagram, provided a simplified view of the annual T-S relationships. The average range of mean monthly temperatures at the surface was found to be 5.6° C and 4.0° C at 50 meters. Salinity at both the surface and 50 meters exhibited a semi-annual periodicity. Range of temperature at 200 meters was 1.5° C. The results of a seasonal linear regression analysis show that surface and 50 meter temperatures were correlated during periods of increasing or decreasing surface temperatures. Surface temperature and salinity were correlated only during the apparent advection of modified subarctic water into the region around OWS November.

14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Surface Temperature						
50 Meter Temperature						
200 Meter Temperature						
Surface Salinity						
50 Meter Salinity						
200 Meter Salinity						
Temperature Salinity Correlations						

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